Mars Sample Return Lander Mission Concepts

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***Abstract*— This paper will provide an overview of current concepts and options for the architecture and design of a Mars Sample Return Lander (called Sample Return Lander, SRL). Key mission objectives and the overall baseline mission design will be described, including the mission's constraints and a notional timeline from launch to entry, through surface operations, to delivery of the samples to Mars orbit. The overall lander vehicle concepts will be described, including current options being evaluated. Key lander element options will be discussed, including the Mars Ascent Vehicle (MAV), Sample Fetch Rover (SFR), Orbiting Sample container (OS), and tube transfer robotics systems. Specific challenges and approaches for addressing those challenges will be discussed, including backward planetary protection.**

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1. INTRODUCTION

This paper is an overview of the current architectural elements for a potential Mars Sample Return (MSR) campaign, and the concepts and options for the architecture and design of a MSR lander, called the Sample Retrieval Lander (SRL), which has been under study since 2017 [1]. Key mission concept objectives and the overall mission design are described, including the mission's constraints and the current notional timeline from launch to entry, through surface operations, to delivery of the samples to Mars orbit. The Earth Return Orbiter (ERO) phase of the mission concept is not discussed in this paper

The two current lander vehicle options being evaluated will be discussed, including the key lander element options of a Mars Ascent Vehicle (MAV), Sample Fetch Rover (SFR), Orbiting Sample (OS) container, and the Sample Transfer Arm (STA) tube transfer robotics systems. Details of the SFR constraints and operations will be discussed.

Specific architecture level challenges and approaches for addressing those challenges are discussed, including backward planetary protection. Major trade studies and specific characteristics are also included.

2. MARS SAMPLE RETURN CAMPAIGN

2.1 Functional Objectives

The functional objectives for a potential MSR campaign include the following:

- Acquire and return to Earth a scientifically selected set of Mars samples for investigation in terrestrial laboratories.
- Select samples based on their geologic diversity, astrobiological relevance, and geochronologic significance.
- Establish the field context for each sample using *in situ* observations.
- Ensure the scientific integrity of the returned samples through contamination control (including round-trip Earth contamination and sample-to-sample cross-contamination) and control of environments experienced by the samples after acquisition.
- Ensure compliance with planetary protection requirements associated with the return of Mars samples to Earth's biosphere.
- Achieve a set of sample-related scientific objectives including: life, geologic environments, geochronology, volatiles, planetary-scale geology, environmental hazards, and In-Situ Resource Utilization (ISRU)

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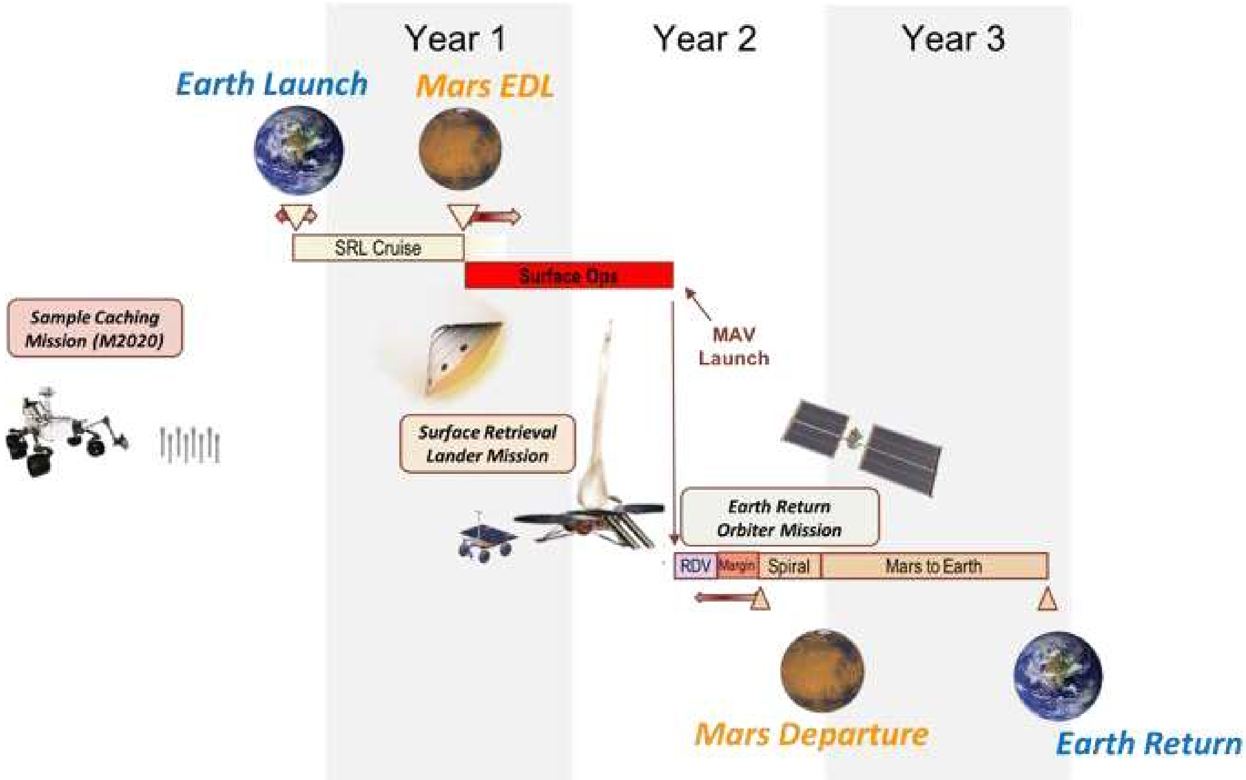

Fig. 1. Potential MSR Mission Scenario.

2.2 MSR Architectural Elements

MSR is currently envisioned to be made up of three flight elements and one ground element. The flight elements include: the Mars 2020 mission, a Sample Retrieval Lander (SRL), and an Earth Return Orbiter (ERO) (including its payload). The ground element would be a Mars Returned Sample Handling (MRSH) facility. Mars 2020 is responsible for sample selection, acquisition and caching. The SRL would include a fetch rover to collect cached samples, the Orbiting Sample (OS) container, into which the sample tubes would be loaded and the Mars Ascent Vehicle (MAV) to launch the OS into Mars orbit. The ERO includes the Capture/Containment and Return System (CCRS), which would capture and contain the OS and transfer it to the Earth Entry Vehicle (EEV) for return it to the surface of Earth. The MRSH facility would receive, quarantine and curate the samples. It would also be responsible for assessing hazards, and providing the opportunities for the international science community to conduct sample science.

2.3 MSR Mission Concept Scenario and Roles

Based on the joint NASA/ESA Statement of Intent (signed in Berlin on 4/26/18) NASA and ESA are studying how to implement MSR in a partnership. The

Mars 2020 rover is being built by NASA/JPL with the planned objective of collecting and caching samples. Per the above agreement, the ERO would be provided by ESA, with the ERO payload provided by NASA. ESA would also provide the SFR and the sample transfer arm (STA) on the NASA provided lander. Figure 1 shows a potential MSR mission scenario with the current architectural elements, their general interfaces and the currently assumed roles.

2.4 Potential Operations Timeline

Figure 2 shows what is referred to as the "fast" MSR timeline, which could return samples as soon as three years after SRL and ERO launch.[2] This timeline is very aggressive in terms of surface operations and ERO orbital operations at Mars. Other timelines are being studied that provide greater flexibility and better design and operational margins.

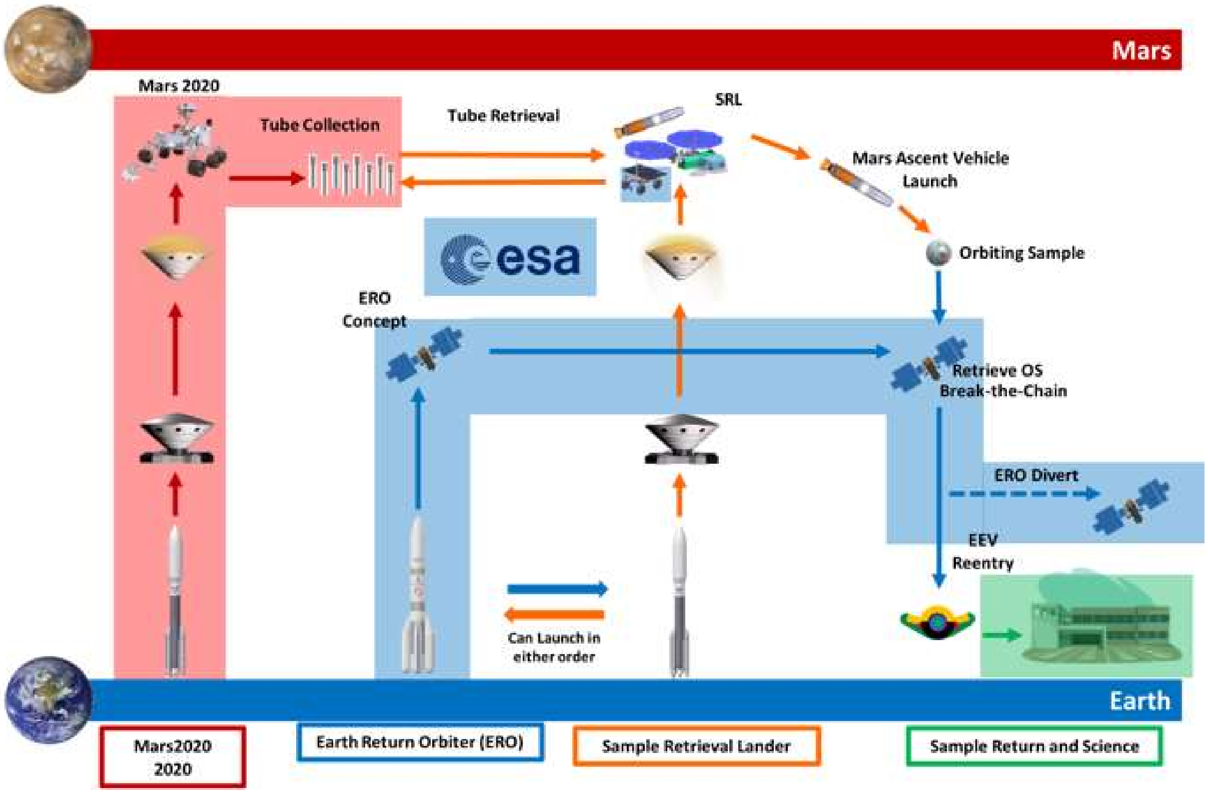

Fig. 2. Notional "Fast" MSR Timeline

2.5 Backward Planetary Protection

The objective of backward Planetary Protection (PP) is to prevent uncontained or unsterilized material from Mars from being released into Earth's environment. This involves a strategy for the use of analysis, design, and testing of the elements and systems that would be implemented and validated/certified to deliver Mars surface sample tubes to Earth; while containing, immobilizing and/or sterilizing any other Mars material that might reach the biosphere of Earth. There are various methodologies used to achieve this objective which is generally referred to as "Break-the-Chain," or BTC.

The key elements of the strategy for BTC that would be applied to both the SRL, ERO and the ERO payloads include:

– Establishing requirements definition approach

– National Environmental Policy Act (NEPA) process

– Use of fault trees for element design

– Use of various modeling tools, including dust transport modelling, to analyze performance and failure modes

– Use of Quantification of Margins and Uncertainties (QMU) for understanding the accuracy of our models

– Use of Probabilistic Risk Assessment (PRA) to support design studies and end-to-end reliability analysis

– Model validation testing

2.5 Key Trade Studies and Systems Engineering

The systems engineering team has developed and maintained a detailed map of trade studies and are assessing options to achieve the most robust end-to-end architecture based on evaluation of the following properties:

- Mission success
- Complexity
- Cost
- Development and operational risk

- Performance
- Implementation approach

Key metrics being used within the trade space and between the elements are:

- Cost, Mass, Power
- Schedule margin (development and operations) including surface timeline, orbital operations timeline
- Planetary protection metrics (e.g. reduction factors, probabilities)
- PRA results initially used for relative comparisons and identification of driving events
- Performance (e.g. # of samples, landing accuracy, delivered surface mass)
- Performance margins (e.g. launch margin, delta velocity (DV) margin, mass margin)

Among the various trade studies the ones around which the entire architecture pivots are:

- OS design (including number of tubes, shape and mass
- Approach and implementation of "Break-the-Chain"
- MAV propulsion technology
- SRL lander approach
- SRL entry, descent and landing approach and any needed augmentations
- ERO propulsion approach and related performance

A key part of the systems engineering process that will be used to close the architecture is the use of Model-Based Systems Engineering (MBSE) for the development and control of the overall concept of operations (Con-ops) starting from the Mars 2020 cache to returning tubes to the surface of the Earth. The Con-ops will go through a thorough evaluation and validation by phase and will be the basis for the functional requirements needed to implement each phase.

The implementation of this cross-Agency and multi-Center systems engineering effort will be facilitated by the following uses of MBSE:

- Provide a reliable, single source of truth for all teams (parameters, function dictionary, etc.)
- Manage systems engineering data across organizations
- Build an integrated system model of technical and programmatic information collaboratively with ESA and other partner NASA Centers
- Have a verifiably consistent model
- Enable analysis of integrated systems engineering data (requirements coverage, PRA)
- Enable reuse by avoiding duplication
- Automated generation of reports & engineering documents

The team is proceeding toward closure of a robust MSR campaign architecture in late 2019.

3. Lander Concepts Under Study

The MSR Sample Retrieval Lander (SRL) team has been actively studying two lander concepts: a Propulsive Platform Lander (PPL) and a Sky Crane Delivered Lander (SDL). The SRL must land on Mars, deploy the Sample Fetch Rover (SFR), and maintain the lander and the MAV within safe operating conditions, including temperatures, while the fetch rover retrieves the M2020 sample tubes. Once the SFR returns with the tubes the following operations would be conducted: transfer tubes to the OS in the MAV Payload Assembly (MPA), using the Sample Transfer Arm (STA); assemble the MPA to the MAV; prepare the MAV for launch (heat to operational temperatures and erect); and execute the MAV launch. The launch sequence would be coordinated between the ERO and ground control and will include the capability for launch abort and retry. The two lander concepts at the time of terminal descent are shown in Figures 3 and 4.

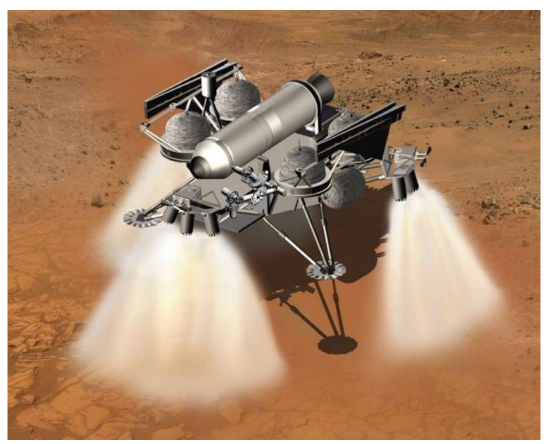

Fig. 3. Propulsive Platform Lander concept at touchdown

Most of the Entry, Descent and Landing (EDL) technology is common to both options and is based on Mars Science Laboratory and Mars 2020. This includes the aeroshell and the parachute system. However, the currently assumed entry is timed at a Mars season of low atmospheric density and would likely require some augmentation of the EDL capability over Mars 2020 to deliver the required mass with appropriate margins. The use of terrain relative navigation (TRN) for landing site targeting, being developed for Mars 2020 will also be a key part of the SRL safe landing approach.

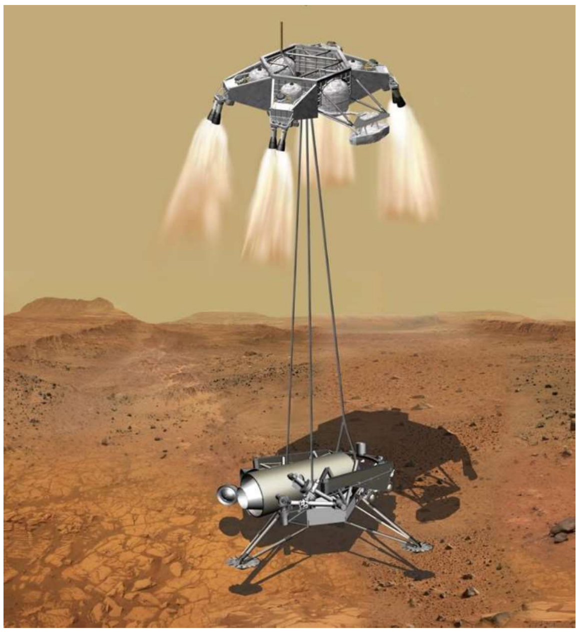

Fig. 4. Skycrane Delivered Lander concept at touchdown

The key elements of the lander are the same regardless of the option. Accommodation of both a MAV (400 kg allocation) and fetch rover (120 kg allocation) within the lander and inside an aeroshell with margins on both mass and volume is currently being studied. Both solar power and thermal design are being considered for the worst-case environments. The MAV propulsion technology, performance (including mass), and reliability is currently being evaluated for multiple propulsion systems (currently a single-stage-to-orbit hybrid and two stage to orbit solid). Several design options for the OS, including tube accommodation and insertion into MAV are being studied. Finally, planetary protection design and implementation strategies to minimize dust contamination and/or sterilize the OS surface are being considered.

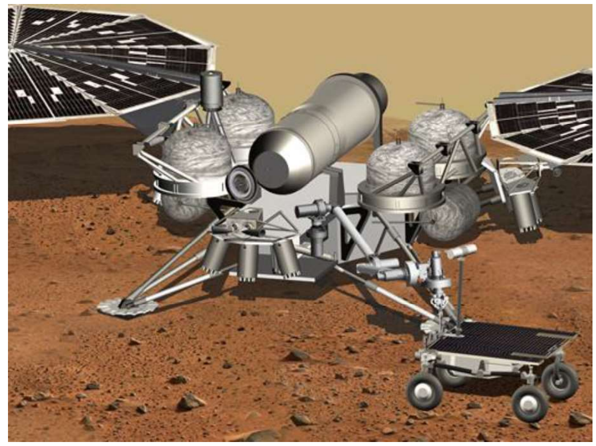

Fig. 5. Propulsive Platform Lander with SFR and STA

The team has come up with initial configurations and structural sizing based on heritage EDL and the accommodation of the MAV and SFR. The SDL concept utilizes heritage Sky Crane EDL from MSL and M2020. The cruise stage is based on the Mars 2020 design with possible updates for the lander mass, the backshell is unchanged, and the descent stage is currently unchanged. Both concepts do, however, utilize a slightly larger, 4.7m spherical heatshield, than what has been used in previous Mars landers. This provides significant additional volume inside the aeroshell that is critical to accommodate the Lander payloads. The PPL concept employs an EDL more similar to Viking or INSIGHT, using the descent and landing propulsion elements from M2020, as part of the platform itself.

Both concepts currently meet functional constraints and have specific advantages/disadvantages. The SDL concept provides a softer landing with less plume/ground interactions due to the Skycrane technology. The PPL concept provides larger configuration and packaging flexibility/margin (in both volume and mass) but presents the complication of potentially significant plume/ground interactions due to the landing thrusters firing closer to the ground (the thruster utilize a shower head nozzle but the ground pressure and effects are still being studied). Both concepts are in the early study phase and require much deeper study and design including into areas such as SFR accommodation, MAV accommodation (including launch) and tube transfer.

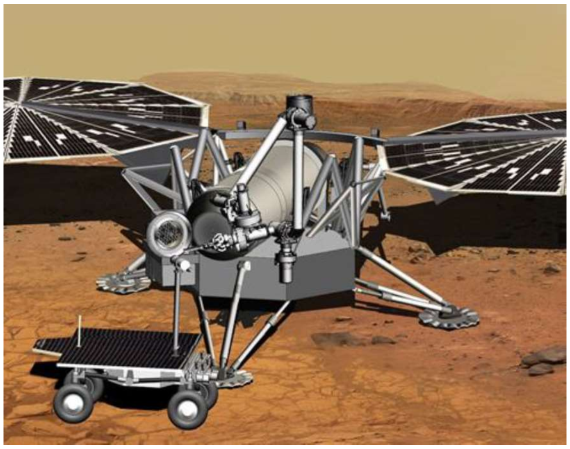

Fig. 6. Skycrane Delivered Lander (SDL) with SFR and STA performing tube transfer

4. Orbiting Sample (OS) and Sample Transfer

The OS must hold desired number of sample tubes as cached by Mars 2020. The final number of tubes and the shape of the OS (e.g. spherical or cylindrical) to be returned is still being traded, but currently ranges from 20 to 30. The maximum assumed mass is 12 kg and diameter is 280 mm. Tubes would be inserted into the OS by the Sample Transfer Arm (STA) on the lander. Current design concepts are working to achieve direct transfer from a tube “tray” on the SFR directly into the OS in the MAV. (See Figures 7 and 8). After the samples have been inserted, the OS then must be closed (i.e. the lid installed and latched) and prepared for launch to orbit by MAV. The tubes need to be secured and maintained through environmental conditions, primarily temperature and dynamics, though Mars launch, Earth return and Earth landing. Constraints placed on the management of the sample tubes by science include maintaining the temperature to less than +30 ºC and magnetic field below ½ mT (at the sample). Additionally, the OS must accommodate rendezvous and tracking by visual wavelength cameras on the orbiter and have sufficient albedo (assumed >0.7) to be detected in Mars orbit.

The details of the rendezvous and capture process and introduction to the processing of the OS for return to Earth are discussed in reference [4].

Fig. 7. Spherical OS concepts for 20 and 30 tube configurations

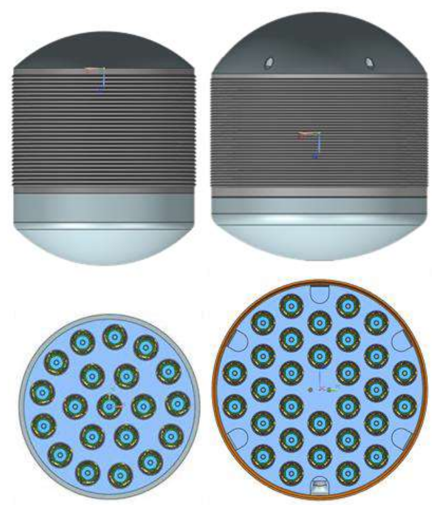

Fig. 8. Cylindrical OS Concepts for 20 and 30 tube configurations

5. MARS ASCENT VEHICLE (MAV) CONCEPT

Numerous propulsion options have been evaluated in the past for the MAV. Most recently these included: single stage monopropellant, liquids and hybrids as well as two stage solids. [3] In 2016, the hybrid option was selected for technology development to mature the novel propellant combination that resulted in both the lowest Gross Lift Off Mass (GLOM) of the study as well as low temperature storage capability.

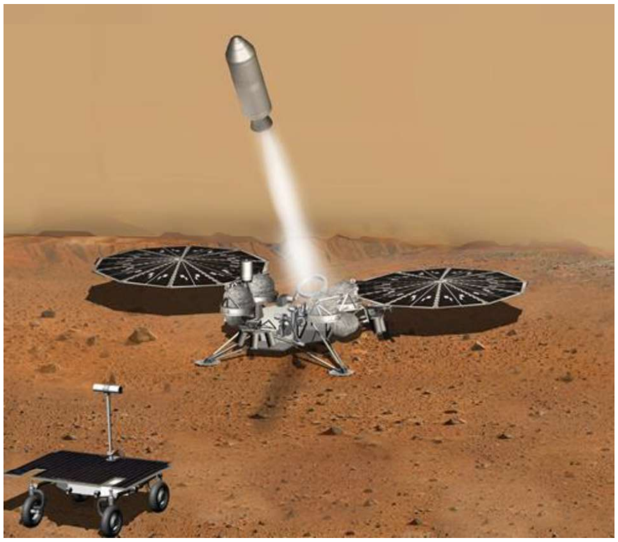

Fig. 9. Propulsive Platform Lander with MAV launch

The concepts for the MAV are currently being developed by a team at JPL and Marshall Space Flight Center (MSFC). The MAV would be responsible for launching the OS from the surface of Mars to a >350 km altitude, and 18-25 degree inclination orbit. Inclination dispersions are currently desired to be maintained below 1 degree; however, this may become more flexible with different ERO options and mission design options. The drivers for the MAV are the launch mass (400 kg) and geometry (3 m long by 0.57 m diameter) in order to fit within the lander described in the previous section.

Currently, two contractors are working together with JPL and MSFC to demonstrate performance of the single stage to orbit hybrid propulsion system using a wax-based fuel and Mixed Oxides of Nitrogen (MON) oxidizer capable of being stored in the variable and low temperature conditions on Mars. The hybrid MAV concept is shown in Figure 10. Moderately high performance, long duration burns (90s), single rest and Liquid Injection Thrust Vector Control (LITVC) have been demonstrated at approximate full scale with the more easily procured MON-3 oxidizer. However, vaporization of the oxidizer has proven to be challenging

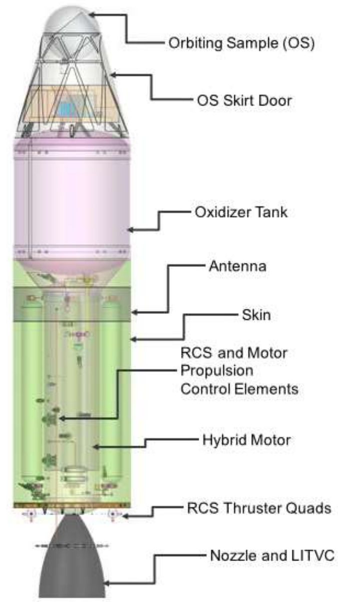

Fig. 10. Hybrid MAV Concept

and additional energy has been used to achieve stable combustion to date. Testing with the desired oxidizer will be carried out in the next year to determine its feasibility for flight.

6. SAMPLE FETCH ROVER CONCEPT

The European Space Agency (ESA) initiated in June 2018 parallel industrial studies for the Sample Fetch Rover (SFR) as a possible contribution to the Mars Sample Return Campaign. The overarching goals of these studies are to demonstrate technical and programmatic feasibility of an ESA rover. The job of the SFR is to acquire Mars material sample tubes, cached by the NASA Mars 2020 mission, from the surface of Mars, and deliver them to the SRL. The SFR interface to the lander and the egress system is being studied jointly by JPL and ESA.

The two competitive parallel studies are managed by Thales Alenia Space Italy and Airbus Defence and Space UK, respectively, and aim at completing phase A/B1 by May 2020. A specific breadboard development will take place with Airbus in order to demonstrate in a field trial the end-to-end operational concept, i.e. the capability to traverse autonomously, pick up the sample tubes and transport them back to the SRL.

Both studies are strongly relying on the ExoMars 2020 mission design heritage. In particular, the ExoMars rover based on a triple bogie, six wheel approach will provide a solid starting point in terms of locomotion system, thermal control, energy management and, autonomous navigation. The ExoMars experience also provides overall industrial, operational and scientific expertise.

The SFR studies also rely on a technology development program, initiated several years ago, the Mars Robotic Exploration Program (MREP), which has led to relevant capabilities in terms of Guidance Navigation and Control (Visual Odometry, mapping, etc.), miniaturised avionics, and low temperature mechanisms and batteries. Additional ESA-led generic technology developments will also be factored in including microprocessors (e.g. Leon 4) and FPGAs (BRAVE).

By mid-November 2018, both contractors will provide their concept for the rover and the egress system. Mass (120 kg NTE for the rover, 25 kg NTE for the egress system) as well as accommodation and volume constraints on SRL are some of the main constraints applied to the system. It is important to note that NASA/JPL and ESA have been working together to define such constraints, while keeping the system trade-offs open at the SRL and MSR campaign level. Due to being in a competitive process, the NASA concept for SFR is shown in Figure 11.

Fig. 11. NASA Concept for Fetch Rover

As mentioned above, ExoMars heritage is a strong starting point as it provides a robust development approach. However, alternatives are also traded-off, e.g. the locomotion systems choice (4 wheels versus 6 wheels, rigid, semi rigid versus compliant wheels, etc.) is being addressed as it may provide advantages, in particular given the volume constraints. The navigation and vision-based fetching are key capabilities for the mission concept, and would very likely demand higher degrees of autonomy than implemented on any current or past rovers, in particular in view of the surface operations timeline and plan to rely only on the ERO for UHF relay. Existing orbiter assets that are part of the Mars Relay Network (MRN including MAVEN, MRO or TGO) may still be available for the SFR surface mission but the approach is to rely on ERO (which will be compatible with the MRN).

Overall, energy availability is the main limitation and on-board efficiency (including operations) will be key to managing the up to 15km (map distance) traverse and sample tube fetching within the 150 sols available for the SFR surface mission.

The possibility of using Mars 2020 as fetch rover was studied. The option was found to be feasible; however, the most robust mission approach was determined to maintain both the fetch rover and Mars 2020.

7. SUMMARY

The MSR campaign architecture trade space is well understood, with reference options defined where appropriate and options are being evaluated to achieve a robust campaign architecture. The major technical elements are at an appropriately detailed level of definition for this phase of a pre-project study effort. Technology development is proceeding per plan. The international and NASA cross-agency team is proceeding toward closure of a robust MSR campaign architecture in late 2019.

ACKNOWLEDGEMENTS

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BIOGRAPHY

Brian Muirhead *has worked on numerous spacecraft and technology projects, including Galileo, SIR-C, and MSTI-1, since coming to NASA's Jet Propulsion Laboratory in 1978. He was responsible for the design, development, test, and launch of the Mars Pathfinder spacecraft that landed successfully on Mars on July 4, 1997. Following this successful landing he was named Project Manager. He served as Project Manager of the Deep Impact Project from November 1999 to November 2002. In November 2002, he became the Chief Engineer of the Mars Science Laboratory mission and in August 2004 he became Chief Engineer of JPL. In February, 2007 Brian was named Program Systems Engineer for the Constellation Program, which includes responsibility for the Lunar Architecture. In 2010 he returned to JPL as Chief Engineer and in 2014 he became the Project Manager of the Asteroid Redirect Robotic mission. He is currently leading the MSR campaign architecture and pre-project efforts.*

He received his BS in Mechanical Engineering from the University of New Mexico in 1977 and an MS in Aeronautical Engineering from Caltech in 1982. He is the recipient of NASA's Exceptional Leadership Medals for his work on Mars Pathfinder and Constellation.

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